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The 6 September 2009 Mw5.4 Earthquake in Eastern Albania – FYROM Border: Focal Mechanisms, Slip Model, ShakeMap

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Abstract: On 6 September 2009 (GMT 21:49) a moderate Mw5.4 earthquake sequence burst at the eastern border of Albania with the Former Yugoslav Republic of Macedonia (FYROM). The main shock was located ~6 km north of the epicentre of the 30 November 1967 Mw6.2 Dibra (or Debar) earthquake, which caused loss of life and considerable damage to buildings. We use broad band waveforms recorded by the Hellenic Unified Seismic Network (HUSN), which receives real-time waveforms from the neighbouring networks, to compute focal mechanisms, obtain the slip model and derive the ShakeMap of the mainshock. The focal mechanisms of 18 of the stronger events of the sequence, obtained through time-domain moment tensor inversion, indicate that deformation is taken up by NNE–SSW-trending normal faults, in agreement with the ~E–W extension previously identified within the Albanian orogen. Our results show that the 2009 main shock ruptured a roughly 9 km normal fault at a depth of 6 km, which strikes at 194° and dips west at ~45°. The slip of the main shock was confined to a single patch of ~9 km × 6 km, the average slip was 5 cm and the peak slip was 18 cm. The slip model was incorporated in a forward modelling scheme to simulate the ground motion distribution in the near field. The ShakeMap thus obtained, based on the distribution of Peak Ground Velocity at phantom stations, outlines the mesoseismal area within the Dibra and Bulqiza districts in Albania, in accordance with macroseismic observations. The region affected by the 2009 sequence, together with the seismogenic region of the 1967 Dibra event, form a roughly NNE–SSW-trending structure which is an active seismotectonic zone in eastern Albania constituting a threat for nearby urban areas.

Key Words: earthquake, Dibra earthquake, slip model, ShakeMap

6 Eylül 2009 Mw5.4 Doğu Arnavutluk – Makedonya Sınırı Depremi: Odak Mekanizmaları, Kayma Modeli, Sarsıntı Haritası

Özet: 6 Eylül 2009 tarihinde (Greenwich saati 21:49) orta büyüklükteki (Mw5.4) bir deprem silsilesi, doğu Arnavutluk ile Makedonya'nın sınırlarını vurmuştur. Depremin ana şoku 30 Kasım 1967'de meydana gelen ve civar yerleşimlerde can ve mal kaybına neden olan Dibra (Debar) depremi (Mw6.2) episantırının yaklaşık 6 km kuzeyinde yer almaktadır. Odak çözümlerini hesaplamak ve kayma modelini elde ederek ana şok sarsıntı haritasını hazırlayabilmek için, komşu ağlardan gerçek zaman dalga formlarını alan Birleşik Helenik Sismik Ağı'nın (*Hellenic Unified Seismic Network*) geniş band dalga formları kullanılmıştır. Zaman baskın ters moment tensör çözümleri ile elde edilen 18 kuvvetli olay dizisine ait odak mekanizmaları, deformasyonun Arnavutluk orojeni içerisinde yaklaşık D–B açılma ile uyumlu olan KKD–GGB yönlü normal faylar tarafından karşılandığını göstermektedir. Bu çalışma 2009 depremine ait ana şokun ~194°D doğrultulu ve ~45° batıya eğimli, kabaca 9 kilometrelik bir normal fayın 6 km derinlikte kırılması ile meydana geldiğini göstermektedir. Ana şoktaki kayma ~9 km × 6 km bir parça ile sınırlanmakta ve ortalama kayma 5 cm ve maksimum kayma 18 cm olmuştur. Yakın alandaki yer sarsıntısı dağılımını simule etmek için kayma modeli, ileri modelleme şeması ile birleştirilmiştir. Maksimum Yer İvmesi dağılımı temel alınarak oluşturulan Sarsıntı Haritası; Arnavutluk'un Dibra ve Bulqiza bölgelerindeki meso-sismik alanın makrosismik gözlemler ile uyumlu olduğunu ortaya koymuştur. 1967 Dibra depreminin sismojenik bölgesi ile 2009 silsilesinin meydana geldiği, kabaca KKD–GGB doğrultusundaki ve doğu Arnavutluk'un aktif sismotektonik zonu olan bu yapı, yakın yerleşim alanları için bir tehlike teşkil etmektedir.

Anahtar Sözcükler: deprem, Dibra depremi, kayma modeli, Sarsıntı Haritası

Introduction

The Albanian mountain belt, a segment of the Dinarides-Hellenides orogen, trends NNW–SSE (Figure 1a) and was developed by Alpine orogenic processes related to the Apulia and Eurasia convergence and the closure of the Mesozoic Tethyan ocean (Kilias *et al.* 2001; Doglioni *et al.* 2007 and references therein). The 6 September 2009 Mw5.4 earthquake sequence, studied here, occurred in the eastern section of the Albanian orogen, near the borders with FYROM, ~55 km ENE of Tirana and ~25 km south of Peshkopie. The sequence had many aftershocks, the strongest of which, at Mw4.1, occurred on 12 September 2009 (GMT18:42). The strongest events of the sequence were adequately recorded by the regional seismological networks of Albania, Greece and FYROM.

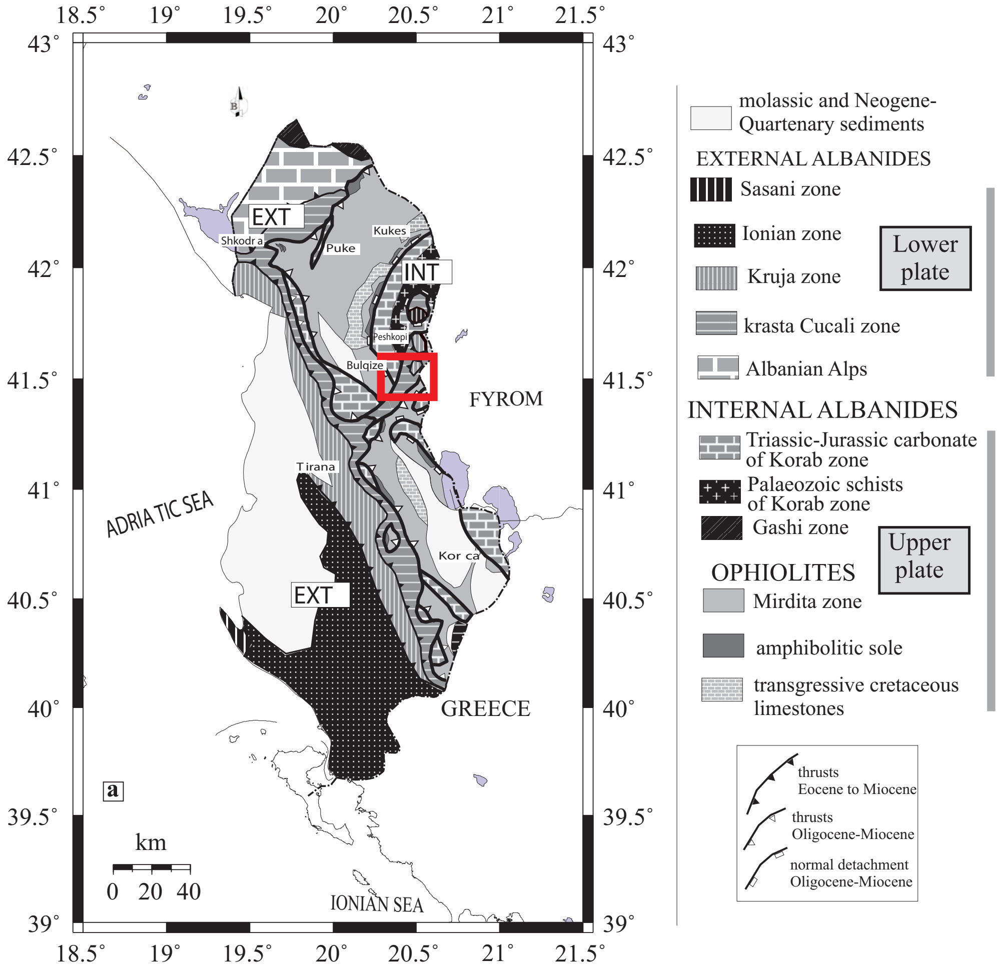

Figure 1. **(a)** Geological sketch map of Albania (from Kilias *et al.* 2001), with the study area marked with a rectangle; **(b)** seismicity (coloured circles) and previously determined focal mechanisms with Mw≥4.0 (both scaled according to magnitude) for the broader region of study. The colouring of the beach-balls denotes different focal mechanisms (e.g., red for reverse/thrust faulting; light green for ~N–S-trending normal faulting; dark green for ~E–W-trending normal faulting; black for strike-slip faulting). The focal mechanism of the 6 September 2009 earthquake confirms the northward continuation of the roughly N–S-trending normal faulting related to the Albanide orogen (extension shown with the diverging arrows), previously well documented by the focal mechanism of the 30 November 1967 Mw6.2 Dibra earthquake (Baker *et al.* 1997). (Focal mechanisms retrieved from Louvari *et al.* 2001; Kiratzi & Louvari 2003 and Kiratzi *et al.* 2007 and the references included in these publications).

The neotectonic faults in the broader region are high-angle normal faults that have variable trends, N–S or NNE–SSW or NNW–SSE (Kilias *et al.* 2001), and this is manifested both in the earthquake focal mechanisms (Figure 1b) and the geomorphology (e.g., Anderson & Jackson 1987; Aliaj 1991; Muço 1994; Louvari *et al.* 2001 and references therein). Moderate size earthquakes are known to have affected

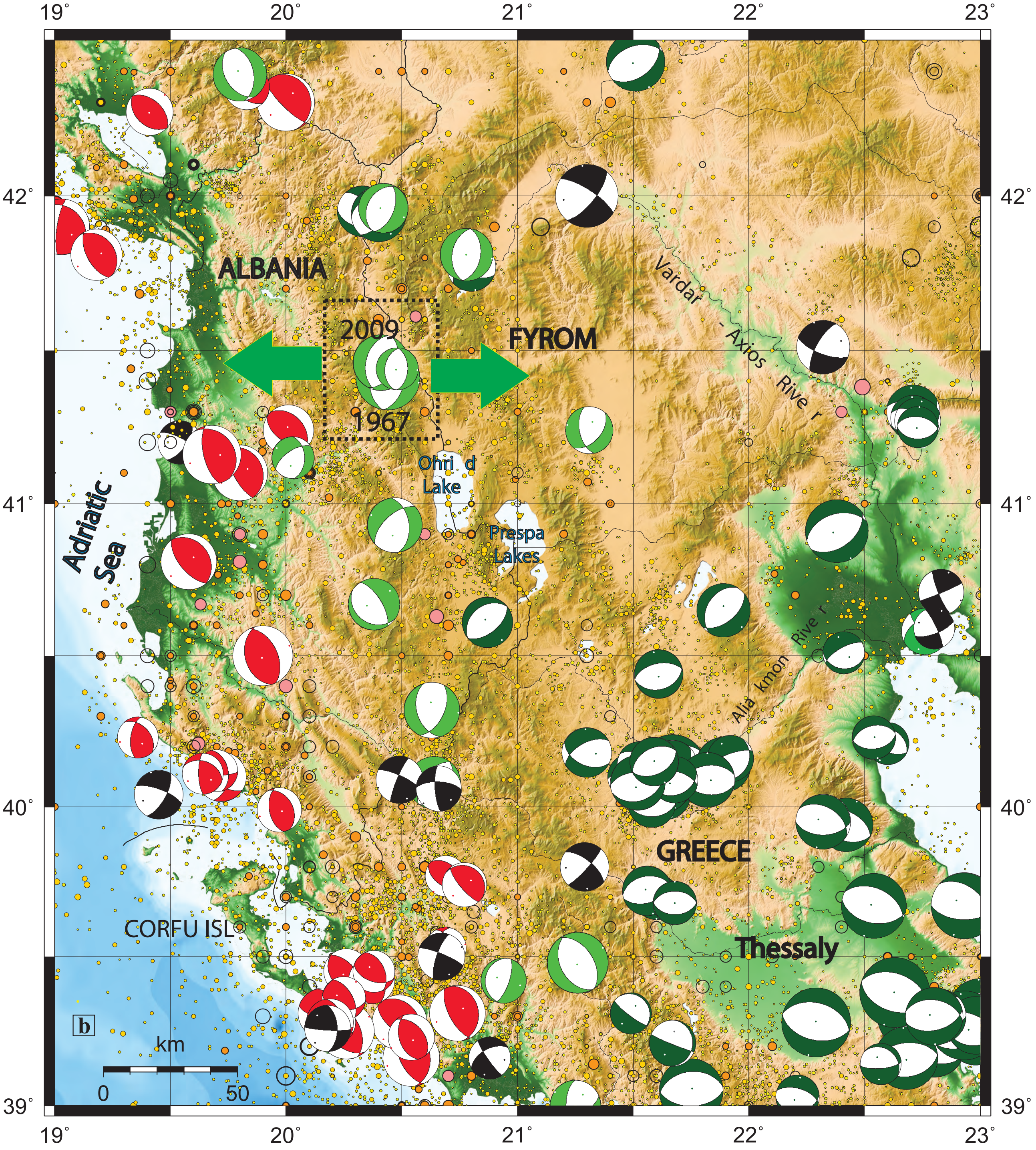

Figure 1. Continued.

the area (Özturk & Ormeni 2009) but their epicentre locations are poorly constrained and the record is considered incomplete since the area is mountainous and remote from major centres of administration and culture.

The previous strong event in the region was the Dibra earthquake of 30 November 1967 (GMT 07:23:50; Mw6.2; 41.41° N 20.44° E; h= 9 km), which caused 19 deaths, 214 injuries and was associated with a N40°E ~10 km discontinuous or eroded surface rupture and 50 cm of vertical displacement (Sulstarova & Kociaj 1980; Ambraseys & Jackson 1998). The focal mechanism solution obtained from waveform modelling (Baker *et al.* 1997) shows normal faulting along NNE-SSW-trending planes with the T-axis indicating roughly E–W extension. The focal mechanism solution based on first motion polarities (Sulstarova & Kociaj 1980) differs from the above mechanism, with the T-axis now having a NNW-SSE orientation (N344°E). Sulstarova & Kociaj (1980) stated that from the two nodal planes of their solution, the one which strikes N40°E and dips 62° to the NW is in accordance both with the surface expression of the fault and the distribution of aftershocks (e.g., their figure 3).

The September 2009 sequence occurred ~6 km north of the Dibra 1967 event (Figure1b) and is probably related to static stress changes caused by this previous strong event, an assumption not tested here. The goal of the present work is to study the source parameters of the 2009 mainshock and its aftershocks in order to shed light to the seismotectonics of the area and the currently active stress field. For this purpose we invert broad band waveform records to calculate (a) moment tensor solutions for 18 events of the sequence; (b) the slip model for the Mw5.4 mainshock and (c) use the derived slip model to calculate the distribution of Peak Ground Velocity (PGV) in order to obtain the Shake Map for the mainshock.

Distribution of Focal Mechanisms

Method Used

Moment tensors of the stronger events of the sequence were computed by the Time-Domain Moment Tensor inversion method (Dreger 2002, 2003). In this approach the general representation of seismic sources is simplified by considering both a spatial and temporal point-source of the form:

$$U_n(x,t) = M_{ij} \times G_{ni,j}(x,z,t) \tag{1}$$

where U_n, is the observed nth component of displacement, $G_{ni,j}$ is the nth component Green's function for specific force-couple orientations, and M_{ij} is the scalar seismic moment tensor, which describes the strength of the force-couples. The general force-couples for a deviatoric moment tensor may be represented by three fundamental faults, namely a vertical strike-slip, a vertical dip-slip, and a 45^0 dip-slip. The indices i and *j* refer to geographical directions. Equation (1) is solved using linear least squares for a given source depth. In the above distribution only the deviatoric seismic moment tensor is resolved, and the inversion yields the M_{ij} which is decomposed into the scalar seismic moment, a double-couple (DC) moment tensor and a compensated linear vector dipole (CLVD) moment tensor. The decomposition is represented as percent DC and percent CLVD. Obviously, percent isotropic (ISO) is always zero for the deviatoric application. The double-couple is further represented in terms of the strike, dip and rake of the two nodal planes. Source depth is found iteratively by finding the solution that yields the largest variance reduction,

$$VR = \left[1 - \sum_i \sqrt{\left(data_i - synth_i\right)^2} \Big/ \sqrt{data_i^2}\right] * 100 \tag{2}$$

where *data*, and *synth* are the data and Green's function time series, respectively, and the summation is performed for all stations and components. It is assumed that the event location is well represented by the high frequency hypocentral location, and a low frequency centroid location is not determined. Moreover, the above simplified representation assumes that the source time history is synchronous for all of the moment tensor elements and that it may be approximated by a delta function. Finally, it is assumed that the crustal model is sufficiently well known to explain low frequency wave propagation.

Application

To apply the method, broad band waveforms were retrieved from the Hellenic Unified Seismic Network (HUSN) which also receives real-time data from the networks of Albania, Montenegro and Bulgaria (Figure 2). Prior to the inversion, full broadband waveforms of the three recorded components were band-pass filtered between 0.05–0.08 Hz or 0.05–0.10 Hz depending on the magnitude of the event and the signal-to-noise ratio of the waveforms. Theoretical Green's functions required to model the propagation of the seismic waves were constructed with the method and code described by Saikia (1994) using the velocity model of Novotný *et al.* (2001), which has proven to successfully describe low frequency wave propagation (e.g., Roumelioti *et al.* 2008a, b, 2010 and references therein).

In Figure 3 we show the moment tensor solution and the waveform fit for the mainshock, while the parameters of the computed focal mechanisms of the aftershocks are listed in Table 1. Figure 4 shows the distribution of the computed focal mechanisms, together with the focal mechanism (Baker *et al.* 1997) of the previously mentioned 1967 Dibra (Debar) earthquake. Normal faulting along ~NNE–SSW-trending planes is dominant, in accordance with the geomorphology, regional focal mechanisms (e.g., Louvari *et al.* 2001; Kiratzi & Louvari 2003 and references therein) and the focal mechanism of the 1967 Dibra earthquake. A number of focal mechanisms are associated with pure strike-slip faulting, reflecting the activation of secondary structures. It is important to note that the activated regions of the 1967 and 2009 sequences indicate that this roughly NNE–SSW-trending structure is an active seismotectonic zone in eastern Albania, following the geomorphology depicted in Figure 4.

Slip Model of the Mainshock

Method

To obtain the slip distribution for the 6 September 2009 mainshock, the finite-fault inversion method of Dreger & Kaverina (2000) and Kaverina *et al.* (2002), a non-negative, least-squares scheme with simultaneous smoothing and damping, was applied. In brief, this method inverts fault slip distributed over a grid of point sources that are triggered according to the passage of a circular rupture front. A Laplacian-smoothing operator, slip positivity, and a scalar moment minimization constraint is applied in all of the inversions. Green's functions based on the Novotný *et al.* (2001) velocity profile, shown to be effective in modelling regional wave propagation, were used to invert the seismic waveforms. As in the previous section the Green's functions were calculated using the frequency-wave number integration method (Saikia 1994) for 1-km intervals in distance and 1-km intervals in depth. The source model used is a single fault plane with constant rupture velocity and constant dislocation rise time.

Application

The seismic data consist of three component broad band displacement waveforms recorded at regional stations of the Greek and neighbouring networks (Figure 2). Both the data and theoretical Green's functions were bandpass filtered between 0.05 to 0.08 Hz. The inversion scheme used here resolves the fault plane ambiguity independent of, and complimentary to, the aftershock distribution and any surface faulting information. In the case studied here the nodal west-dipping plane (e.g., the one with strike of 194°) resulted in larger variance reduction (VR= 85%) compared to the east dipping plane (VR= 81%), and was assumed to be the fault plane for the slip inversions. This implies that the azimuth of the slip vector is 295° and its plunge 44°. From a standard grid search of the parameter space, the rupture velocity was found to be 2.7 km/s and the rise time 0.3 s. The results of the inversion show that slip is confined in a single patch, and the maximum slip is located ~3 km to the NNE of the hypocentre location (Figure 5). Average slip in the ruptured area is ~5 cm and peak slip reaches 18 cm to the NNE of the hypocentre. The scalar seismic moment for the slip model is $M_o= 1.38\times10^{24}$ dyn-cm, in good agreement with the scalar moment obtained in the moment tensor solution (Figure 3) confirming the magnitude of the event (Mw5.4). The total data variance reduction for the solution, calculated as a normalized squared misfit, is 85%, indicating a satisfactory level of fit (Figure 6).

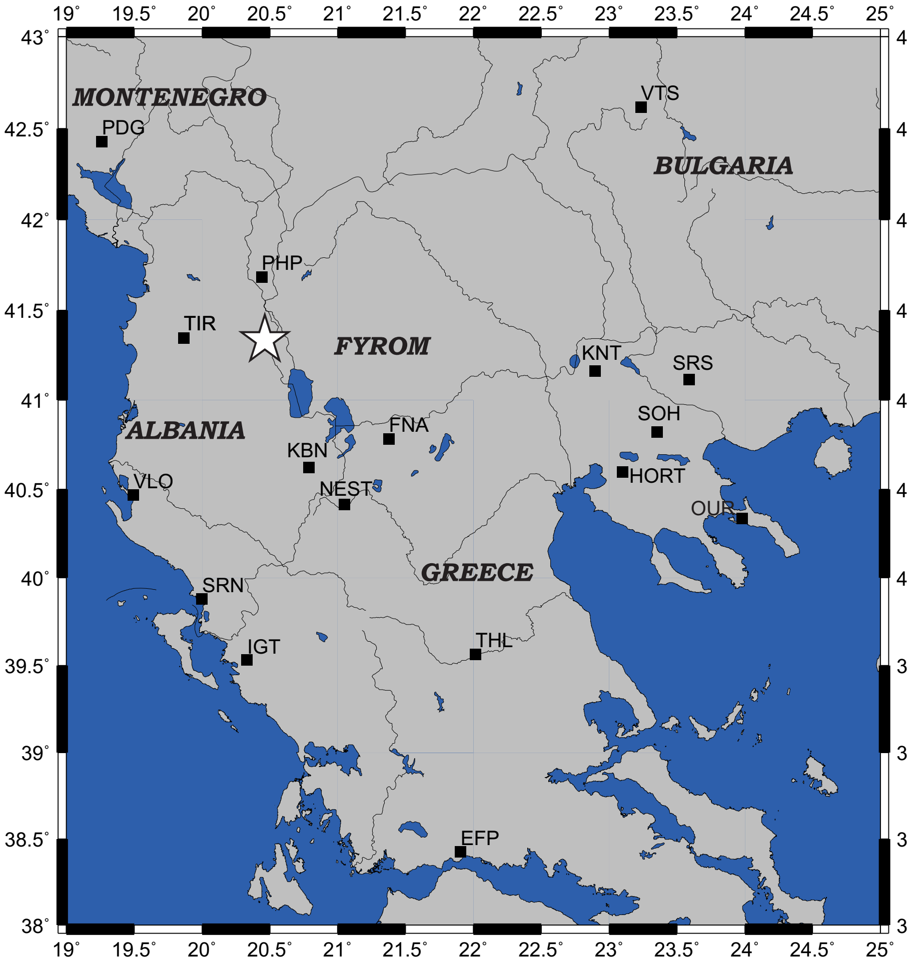

Figure 2. Geometry of the stations (squares) whose waveforms were used in the time-domain moment tensor inversion to obtain focal mechanisms and/or in the finite-fault inversion to obtain the slip model of the main shock (star). Station codes listed next to the stations.

Prediction of Ground Motion (Shake Map) of the Mainshock

During this stage the derived slip model (Figure 5) was incorporated in the forward calculation of velocity time histories at the nodes of a grid 50 km × 50 km centred at the epicentre location. The forward modelling was performed using the code of Kaverina *et al.* (2002) as it was further developed for applications in the Aegean Sea region (e.g., Roumelioti *et al.* 2008b and references therein). Full velocity waveforms up to 5 Hz were computed, for the two horizontal components, and their peak values (PGV in cm/s) were retrieved to construct the Shake Map showing the spatial distribution of strong ground motions. Site effects at the nodes of the grid, which in the present case are important since the entire mesoseismal region is dominated by limestone or flysch deposits, were taken into account using the topography gradient as proxy for the site categorization, based on shear-wave velocities Vs_{30}, a procedure suggested by Wald & Allen (2007). Thus for each node we obtain the value of Vs_{30} – an indicator of the site effect. Then we use the site categories of NERHP (1994) and Klimis *et al.* (1999) and as a next step we apply the frequency and amplitude dependent amplification factors, for intermediate frequencies, determined by Borcherdt (1994).

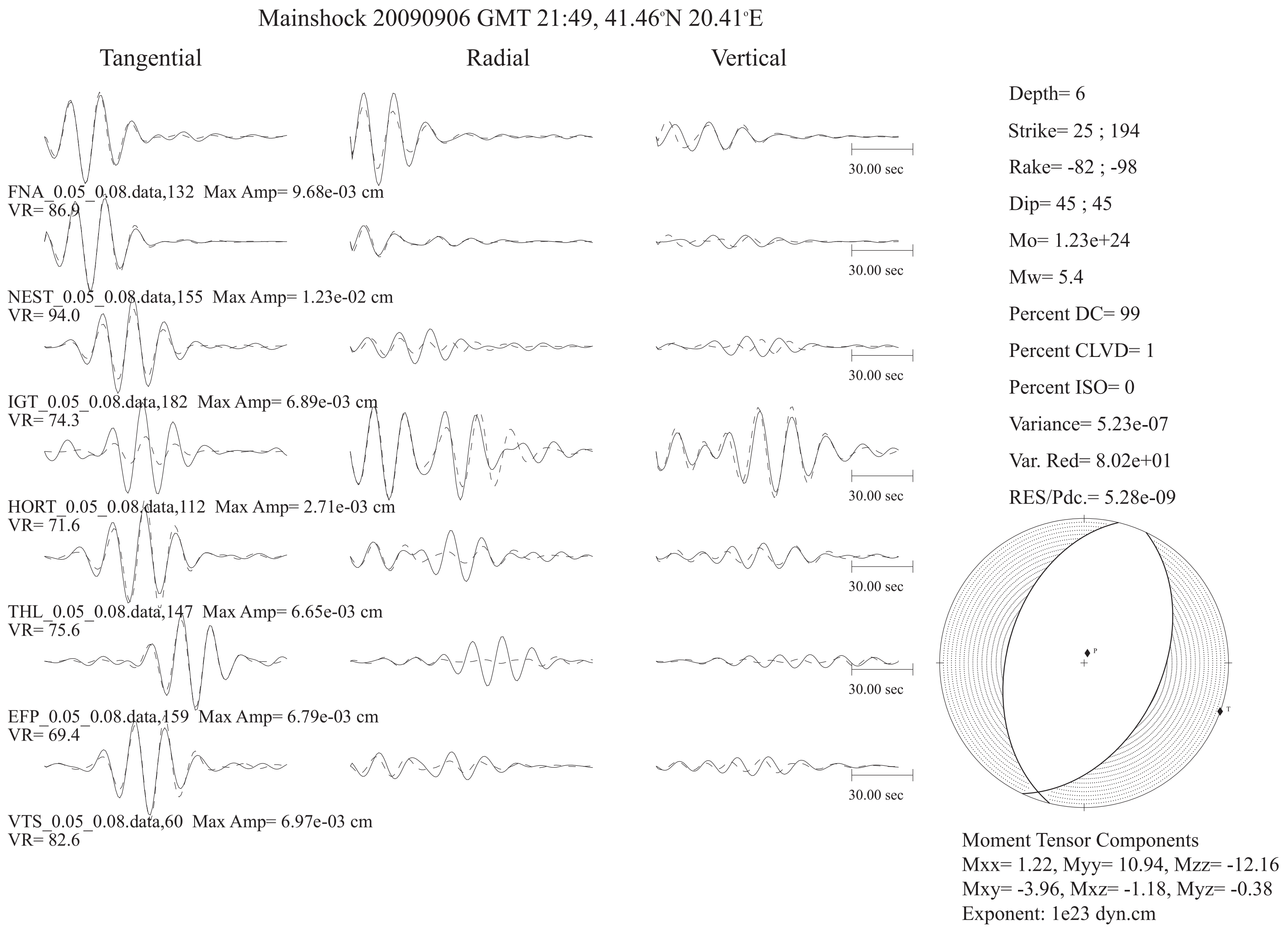

Figure 3. Moment tensor solution for the 6 September 2009, GMT 21:49 main shock (No 1 in Table 1). For each station the waveform fit between observed (continuous lines) and synthetic (dashed lines) vertical, tangential and radial components is shown. Solution parameters are summarized in the right part of the figure.

Table 1. Source parameters for 18 aftershocks of the 6 September 2009 Mw5.4 Dibra sequence in Albania (epicentre locations are from EMSC and the on-line archive of the Department of Geophysics of the Aristotle University of Thessaloniki, http://seismology.geo.auth.gr). CLVD and VR list the percentage of the Compensated Linear Vector Dipole and of the Variance Reduction, respectively. The last line lists the parameters for the previous 1967 Mw 6.2 Dibra event (from Baker *et al.* 1997).

No	Date	Origin Time	Lat	Lon	h	M_w	Nodal Plane 1			Nodal Plane 2			P axis		T axis		CLVD	VR
	YY/MM/DD	hh:mm:ss	(ºN)	(ºE)	(km)		Strike	Dip	Rake	Strike	Dip	Rake	az	dip	az	dip	%	%
1	20090906	21:49:42	41.46	20.41	6	5.4	194	45	-98	25	46	-82	14	84	110	1	1	80
2	20090906	22:24:43	41.53	20.48	9	3.9	31	67	-81	189	25	-110	318	67	114	21	35	66
3	20090906	22:36:05	41.47	20.49	4	3.6	119	40	-86	294	50	-93	180	84	26	5	4	57
4	20090906	23:31:32	41.50	20.47	3	3.2	346	31	-157	236	78	-61	177	49	303	27	3	65
5	20090906	23:59:02	41.52	20.41	2	3.4	210	76	-75	342	20	-136	139	56	288	30	11	78
6	20090907	00:06:58	41.53	20.45	9	3.0	162	86	-176	72	86	-4	27	6	117	0	18	69
7	20090907	00:11:14	41.47	20.47	6	3.7	42	57	-72	191	37	-116	356	72	119	10	8	82
8	20090907	00:34:25	41.45	20.47	6	3.4	32	56	-85	203	34	-97	320	78	118	11	31	65
9	20090907	09:48:38	41.50	20.47	13	3.5	17	47	-70	169	47	-110	3	75	93	0	30	80
10	20090907	12:21:46	41.44	20.47	8	3.3	210	87	-174	120	84	-3	75	6	345	2	16	50
11	20090907	13:42:31	41.46	20.46	3	3.2	345	52	-78	146	40	-105	304	79	66	6	11	77
12	20090907	15:20:30	41.46	20.50	4	3.6	11	43	-92	194	47	-88	139	88	283	2	34	88
13	20090907	20:24:36	41.46	20.49	4	3.7	21	45	-72	176	48	-107	15	77	278	2	3	88
14	20090907	22:15:32	41.48	20.48	5	3.7	33	55	-87	208	35	-94	314	80	121	10	19	68
15	20090912	18:42:55	41.44	20.48	6	4.1	1	49	-94	187	41	-85	237	85	94	4	14	79
16	20090919	13:09:10	41.54	20.48	2	2.5	331	55	-97	163	36	-80	214	79	66	10	1	44
17	20090925	11:57:12	41.53	20.48	15	3.2	42	66	168	137	79	24	268	9	2	25	1	57
18	20091002	04:47:14	41.40	22.49	3	3.0	86	35	-32	203	72	-121	76	53	316	21	23	59
	19671130	07:23:50	41.410	20.440	9	6.2	190	43	-88	7	47	-92	242	88	98	2		

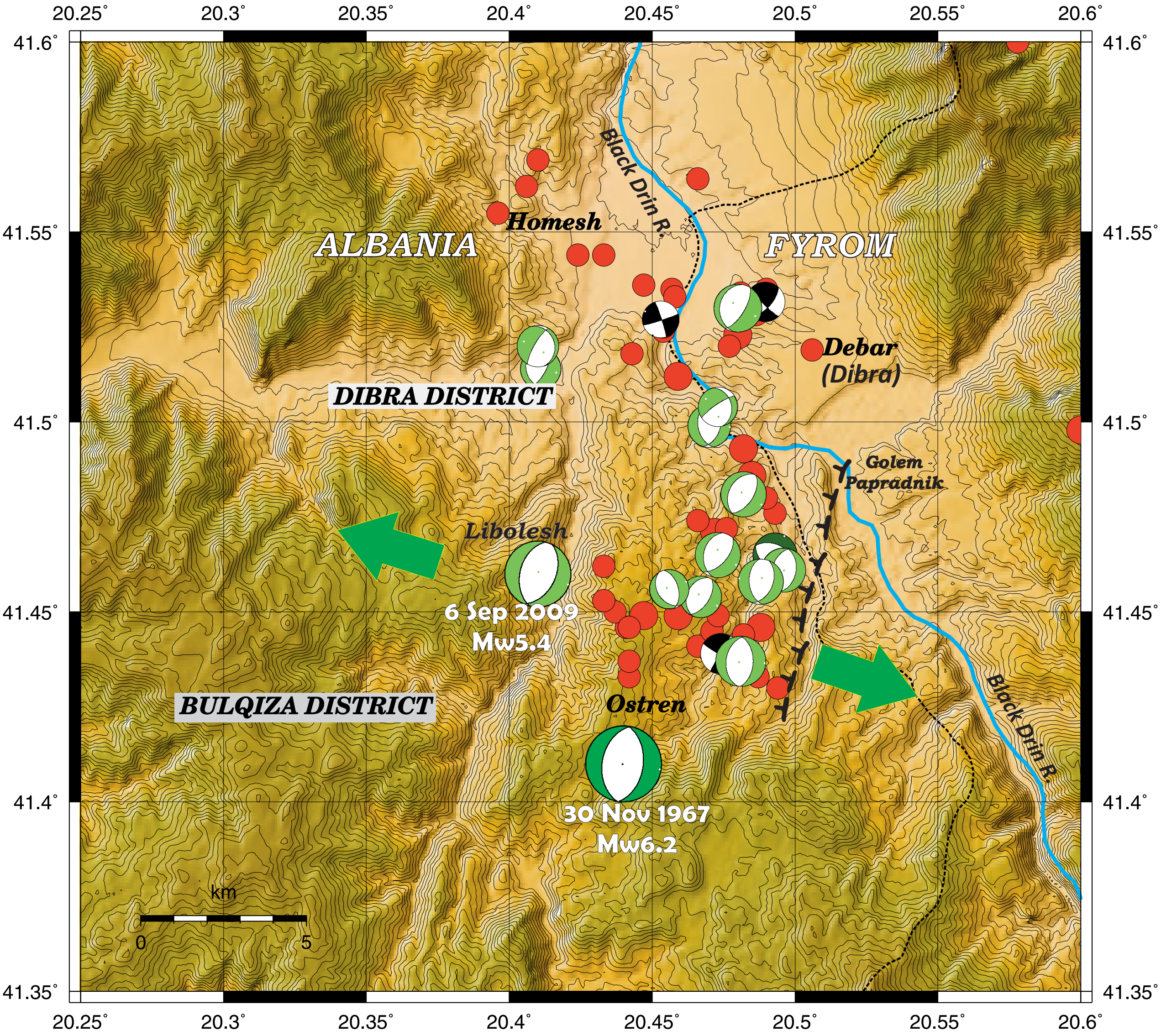

Figure 4. Focal mechanisms of the strongest aftershocks of the 2009 sequence (Table 1) together with the focal mechanism of the previous 30 November 1967 Mw6.2 event (beach-ball colouring as in Figure 1b). The estimated surface projection of the fault that ruptured during the 2009 main shock is indicatively shown with the hatched line. The 2009 sequence confirms the roughly E–W extension of the Albanian orogen. Aftershock locations (red circles) for the period 6 September to 31 December 2009 have been retrieved from the on-line catalogue of the Aristotle University of Thessaloniki (http://seismology.geo.auth.gr).

In Figure 7 the Shake Map obtained from the distribution of PGV values, which are considered a good indicator of the damage, and the relations of Wald *et al.* (1999) shows that the mesoseismal area extends mainly to the NNE of the epicentre, in the boundaries of Dibra and Bulqiza Districts of Albania and the nearby town of Debar (also known as Diber or Dibra) in FYROM. The slip model used to construct the Shake Map predicts moderate to heavy damage in these regions. A preliminary macroseismic report provided by the Institute of Geosciences in Tirana, stated that a total of 179 houses suffered moderate to heavy damage and all are in the Dibra and Bulqiza districts of the region, well depicted by the most

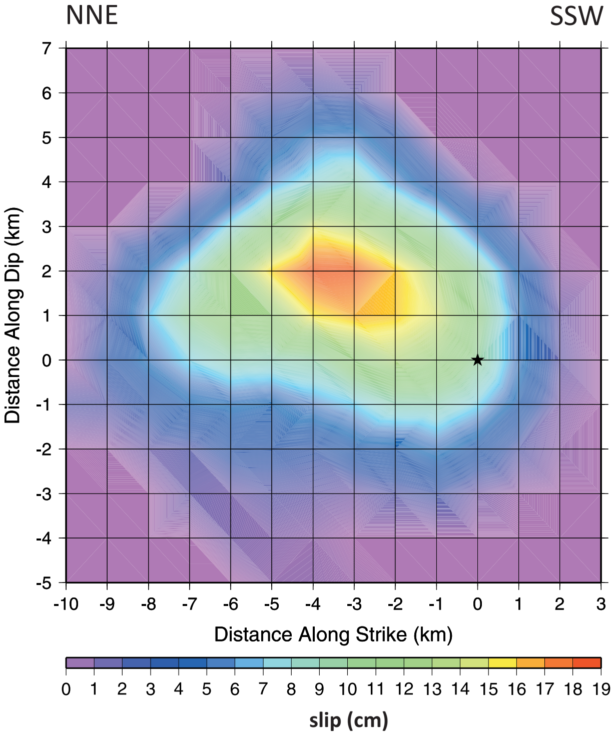

Figure 5. Slip distribution for the 6 September 2009 event onto the westward dipping plane (i.e. the nodal plane that strikes N194°E and dips 45° to W in Figure 4). The slip area (9 km × 6 km, along strike and along dip, respectively) expands mainly to the NNE of the hypocentre (star). The slip model was obtained for a rupture velocity of 2.7 km/sec and a rise time of 0.3s. Note that the coordinates (0, 0) in this figure correspond to the rupture initiation point on to the plane, which is at a depth of 6 km obtained from the moment tensor solution (Figure 3). Average slip is roughly 5 cm while the peak slip is calculated to be 18 cm.

affected part determined here. The Shake Map has a NNE–SSW elongation towards the town of Debar in FYROM, exactly like the one observed in the isoseismal map (intensity VIII) of the 30 November 1967 Dibra event (Sulstarova & Kociaj 1980; Muço 1994).

Conclusions

We have studied the 6 September 2009 Mw5.4 Dibra earthquake sequence in eastern Albania near its borders with Fyrom. The epicentre of the mainshock occurred roughly 6 km north of the 30 November 1967 (Mw 6.2) Dibra earthquake. Time-domain full moment tensor inversion of broad band waveforms was used to calculate the focal mechanisms of 18 aftershocks of the sequence which confirmed the regional E–W extensional stress field. The mainshock of 6 September 2009 ruptured a normal fault of 9 km × 6 km, along strike and along dip, respectively, dipping west at 45°. The hypocentre is located at a depth of 6 km. Finite-fault inversion of broad band waveforms indicated that the fault plane slip is confined to a single patch, in which the average slip is 5 cm and the peak slip is 18 cm, in accordance with the empirically expected values for a Mw5.4 earthquake. The slip model was subsequently used to perform forward calculations over a grid covering the broader region, in order to predict the distribution of strong ground motion. The Shake Map obtained from the spatial distribution of the peak values of ground velocity predicts the spatial extent of the mesoseismal area between the Dibra and Bulqiza districts in Albania exhibiting also a NNE prolongation towards the town of Debar in FYROM. The damage predicted is in accordance with the preliminary macroseismic report for the 6 September 2009 earthquake. The fact that the epicentre of the 2009 event is close to the previous 30 November 1967 Mw6.2 earthquake probably reflects the genetic relation of these two events through the ideas of static stress changes, something not tested in this work.

The Dibra 2009 sequence confirmed the northward continuation of the normal faulting along roughly NNE–SSW-trending faults, related to the Albanide orogen belt (Louvari *et al.* 2001; Kilias *et al.* 2001 among others). In fact, the available focal mechanisms of the earthquakes with Mw≥4.0 (e.g., Figure 1b), indicate that the present day deformation in western Albania is taken up by normal faults that trend from N–S to NNE–SSW. Recent studies (Caporali *et al.* 2009) have geodetically identified a large-scale right-lateral shear zone crossing Albania. However, the seismicity data and more specifically the focal mechanisms of the stronger events do not indicate any shear motions in Albania. A limited number of fault plane solutions for events with Mw less than 4.0 does show shear motions (Kiratzi *et al.* 2007), but small magnitude events may not reflect regional tectonics. The underlying process of the E–W-trending extension along the Albanide orogen, which continues along the Hellenide orogen in the south, is still open to discussion. For example, the

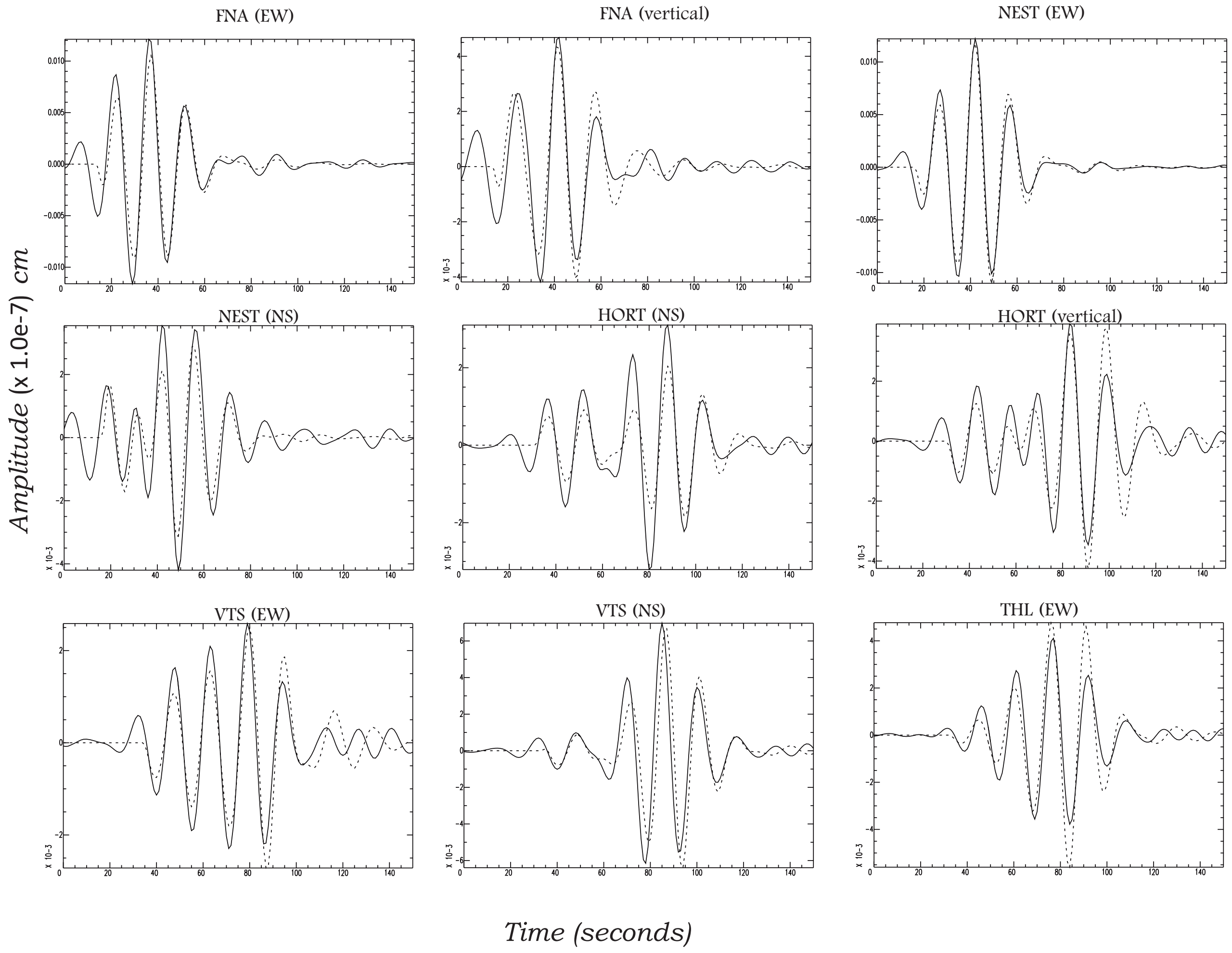

Figure 6. Predicted (dashed lines) displacement broad band waveforms, which were calculated using forward modelling and the derived slip model, and their fit to the observed (straight lines). Both the data and synthetics have been bandpass filtered between 0.05 to 0.08 Hz. The station code and the corresponding component are also shown in the plots.

extension is interpreted as gravitational collapse of the orogen (e.g., Dewey 1988) or slab roll-back (e.g., Royden 1993; Jolivet & Facenna 2000) or slab detachment (e.g., Wortel & Spakman 2000). More recently, Copley *et al.* (2009) suggested that the sub-parallel thrusting and normal faulting in Albania are likely to be the result of gravitational potential energy differences between the lowlands of western Albania and the mountains in the east of the country. More specifically they discussed the possibility that the deposition of large thicknesses of sediment in western Albania and the Adriatic Sea throughout the Mesozoic and Cenozoic may have weakened the crystalline lower crust and upper mantle by increasing the temperature, and therefore reducing the potential energy contrast supportable by the lowlands. This may have led to the normal faulting currently occurring in the mountains of eastern Albania.

Acknowledgments

Moment tensors were computed using the tdmt-invc package developed by Douglas Dreger of the Berkeley Seismological Laboratory, and Green's functions were computed using the FKRPROG software developed by Chandan Saikia with URS Granger, Woodward Clyde Federal Services. Maps

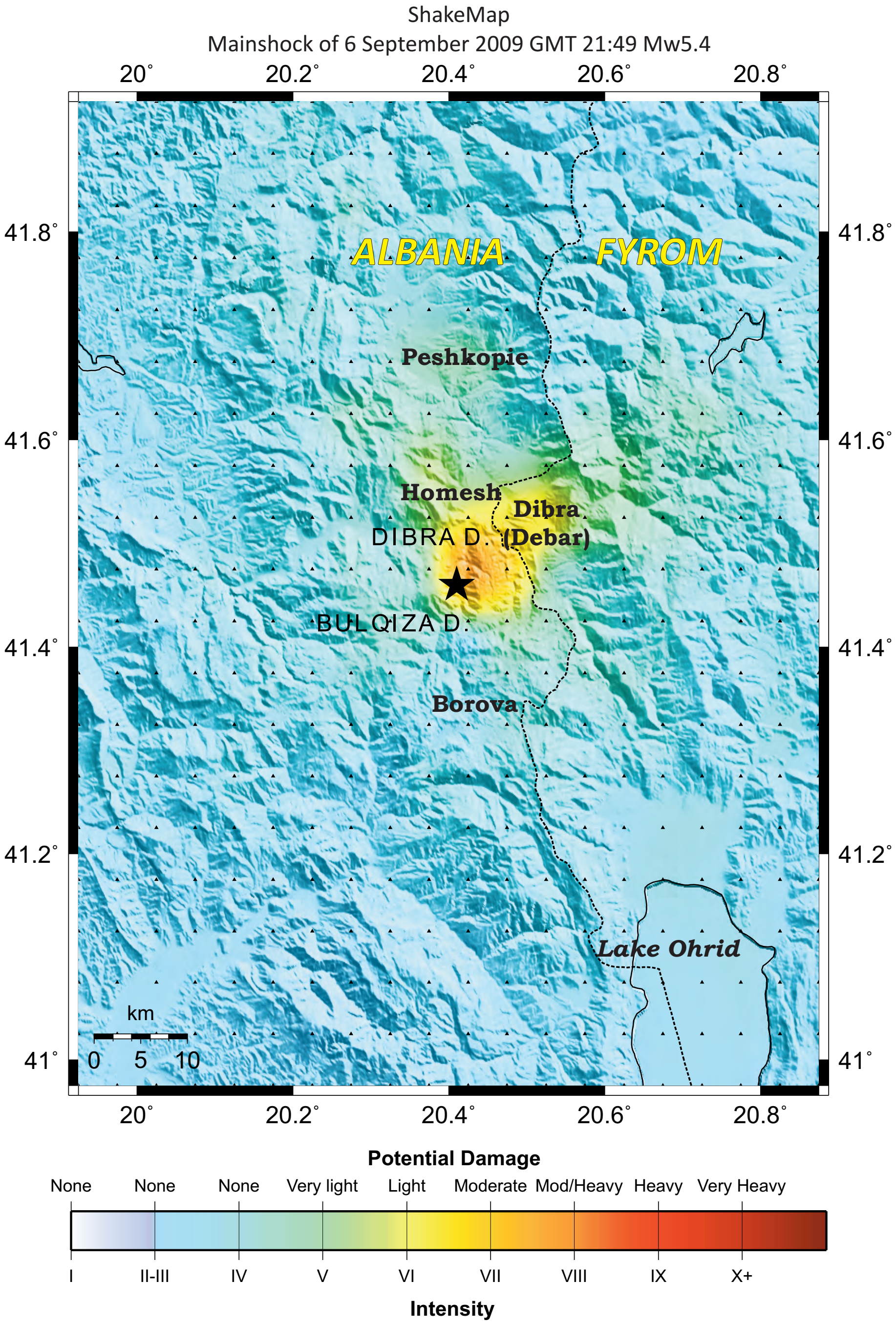

Figure 7. Shake Map for the 6 September 2009 Mw5.4 mainshock (the star denotes the epicentre) calculated from the distribution of synthetic horizontal PGVs. Synthetic time series of ground velocity were calculated at phantom stations (denoted with black triangles) over a grid covering the broader region, using forward modelling and the here calculated slip model (Figure 5). The mesoseismal area is well depicted in the borders of the Bulqiza and Dibra districts of Albania towards the town of Debar (or Dibra) in FYROM and is exactly in the mesoseismal region where over 100 residences were heavily damaged. Both the slip model and the Shake Map suggest rupture directivity, if any, was towards the NE.

were produced using the GMT software (Wessel & Smith 1998). Seismic Analysis Code (SAC) was used to process the data. Special thanks are also extended to D. Kilias for providing Figure 1a, and to three anonymous reviewers whose suggestions improved the original submission. Data sources: Broad band waveforms were retrieved from the Hellenic Unified Seismic Network (HUSN) which also receives real-time waveforms from neighbouring networks, e.g., from Albania, Bulgaria and Montenegro used here. The preliminary macroseismic report can be retrieved from EMSC (http://www.emsc-csem.org/current/evt/ALBANIA_138961.pdf).

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